

# Coordinated Vehicle Platooning with Multiple Speeds

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November 13, 2018

# Computationally Enhanced Mobility



- ▶ Developing high-fidelity simulation tools to estimate the energy impact of Connected and Automated Vehicles.
- ▶ Developing algorithms for optimally routing vehicles with platooning capabilities.

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- ▶ Developing algorithms for optimally routing vehicles with platooning capabilities.

▶ POLARIS



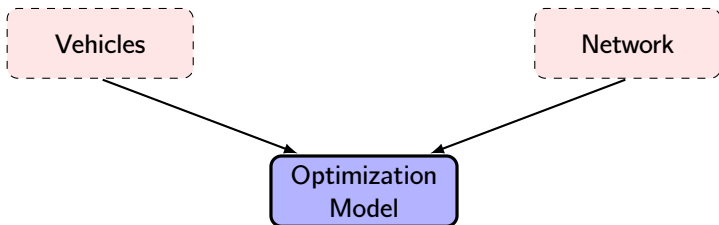
# Workflow

Vehicles

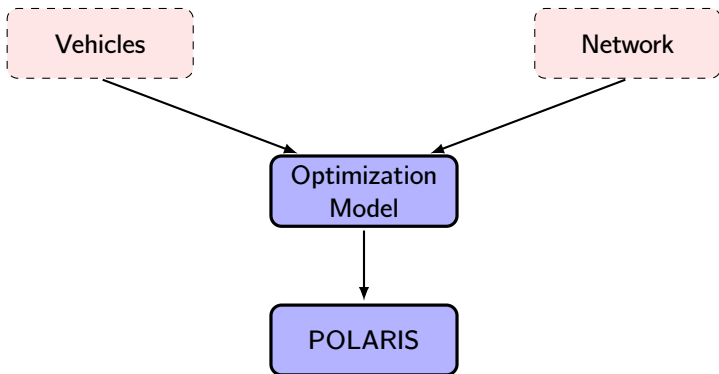
Network



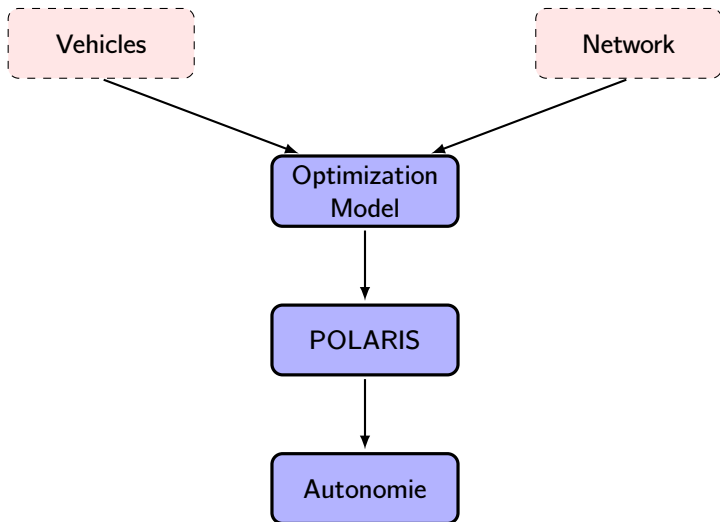
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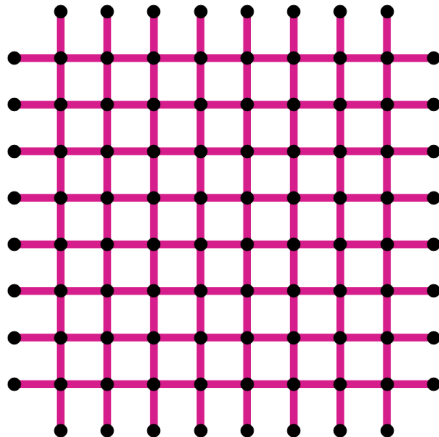
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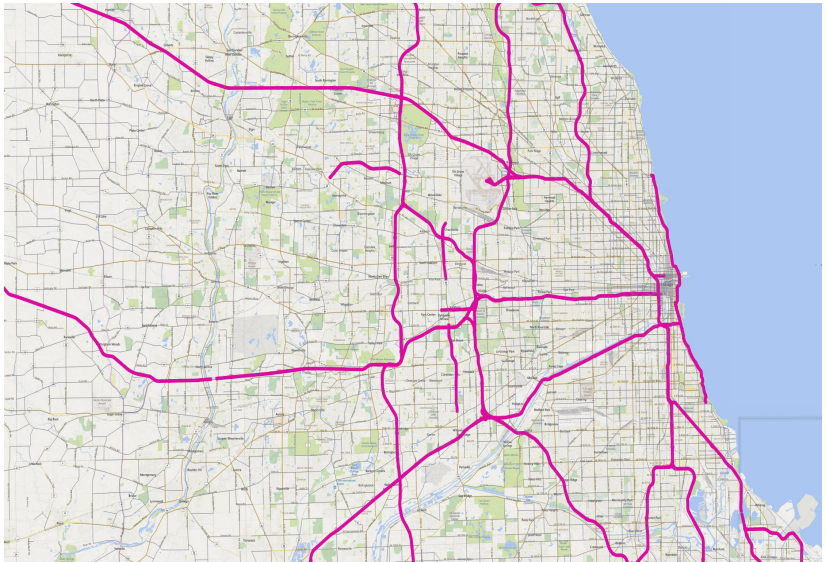
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# Optimization Model - Model Parameters

Set	Meaning
$V$	Vehicles to route
$I$	Network nodes
$E \subseteq I \times I$	Network edges



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Parameter	Meaning
$O_v$	$v \in V$ origin node
$D_v$	$v \in V$ destination node
$T_v^O$	$v \in V$ origin time
$T_v^D$	$v \in V$ destination time
$C_v^W$	waiting cost for $v \in V$
$C_{i,j}$	cost for taking $(i,j) \in E$



# Optimization Model - Model Variables

Variable	Meaning
$f_{v,i,j}$	1 if $v$ travels on $(i,j)$
$q_{v,w,i,j}$	1 if $v$ follows $w$ on $(i,j)$
$e_{v,i,j}$	Time $v$ enters $(i,j)$
$w_{v,i}$	Time $v$ waits at $i$



# Optimization Model - Model Constraints

Node outflows must equal inflows.

When platooning, enter times are equal.

Platooning requires at least two vehicles.

Only one vehicle can follow.

$T_v^O$  plus waiting time is the origin enter time.

$T_v^D$  is the final enter time plus the time required to travel the final edge plus waiting at the end.

Intermediate enter times are equal plus the travel and waiting times.

Can't have nonzero enter time if there is no flow.

Can't have nonzero wait time if there is no flow.

Platoon requires flow for the leader.

Platoon requires flow for the followers.



# Optimization Model - Example Constraints

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$$e_{v,i,j} \leq Mf_{v,i,j}; \quad \forall v \in V, (i,j) \in E$$



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$$-M(1 - q_{v,w,i,j}) \leq e_{v,i,j} - e_{w,i,j} \leq M(1 - q_{v,w,i,j})$$



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Objective:

$$\text{minimize} \quad \sum_{v,i,j} C_{i,j} \left( f_{v,i,j} - \eta \sum_w q_{v,w,i,j} \right) + \sum_{v,i} C_v^w w_{v,i}$$



# Animations

▶ Grid

▶ Chicago



# Helping the MIP solver



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Consider  $v$  and  $w$  platooning on edge  $(i, j)$  only if

$$\max \{ T_v^O + M_{O_v, i}, T_w^O + M_{O_w, i} \} + T_{ij} \leq \min \{ T_v^D - M_{D_v, j}, T_w^D - M_{D_w, j} \}$$

where  $M_{a,b}$  is the minimum time required to reach  $b$  from  $a$ .



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## Lemma

*If vehicles use a fraction  $\eta$  less fuel when trailing in a platooning and  $t_s$  is the shortest time for a vehicle to travel from its origin to destination, it will never travel a path longer than  $\frac{1}{1-\eta} t_s$ .*



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## Lemma

*There exists an optimal platoon routing in which no two vehicles split and then merge together.*



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- ▶ Destination times

$$T_D^v = T_O^v + M_{O_v, D_v} + p,$$

for some time  $p \geq 0$



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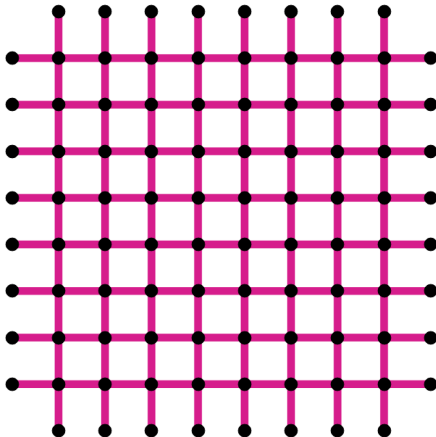
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- ▶ 10 replications



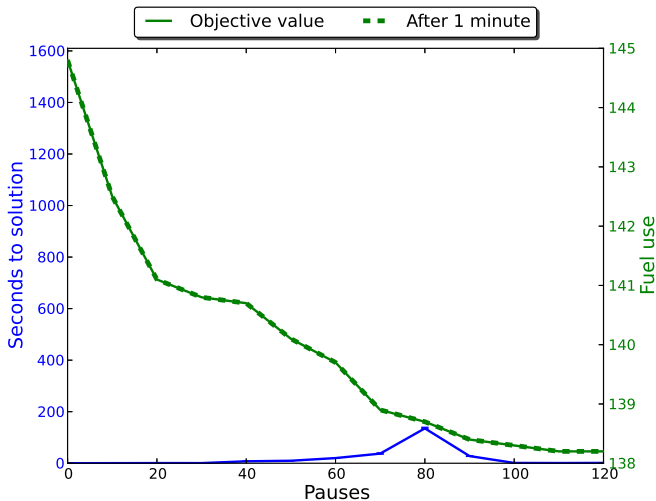
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- ▶ 10 replications
- ▶ Running Gurobi until its optimality gap is less than  $1e-8$

## Example solution times



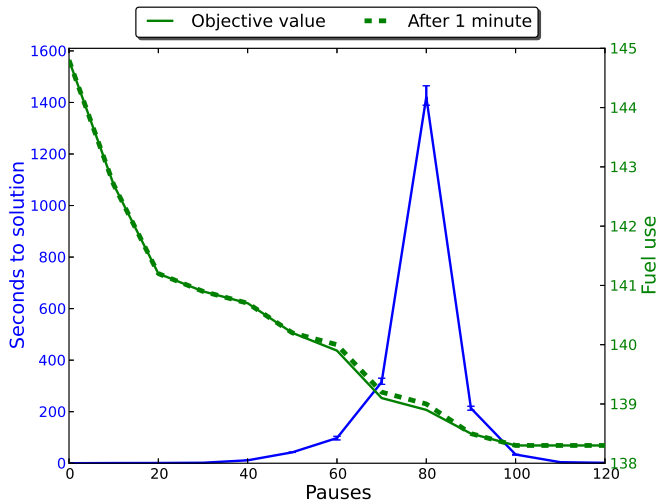
# Example solution times



Grid, waiting allowed at intermediate nodes

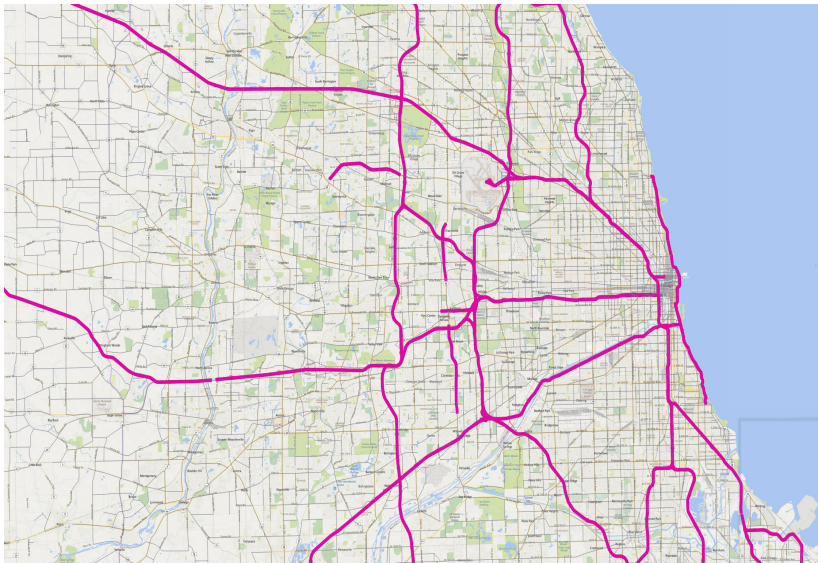


# Example solution times

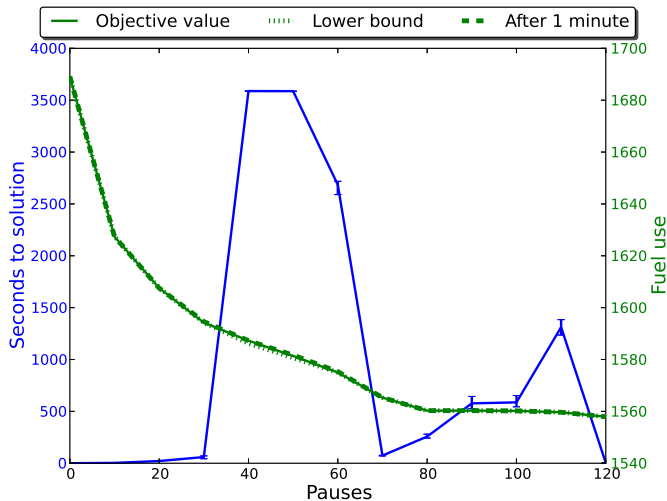


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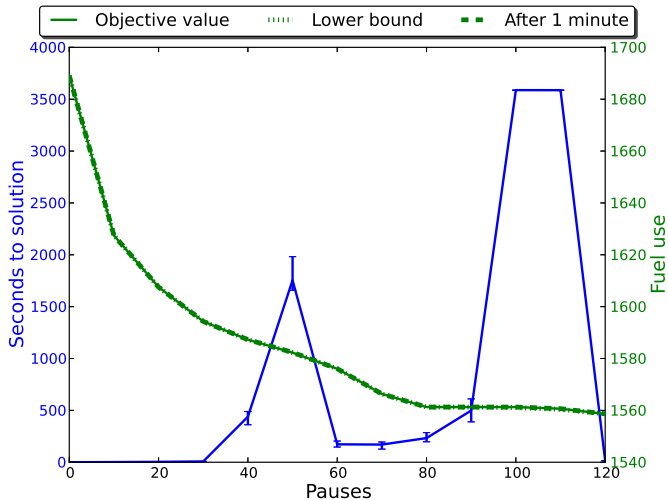
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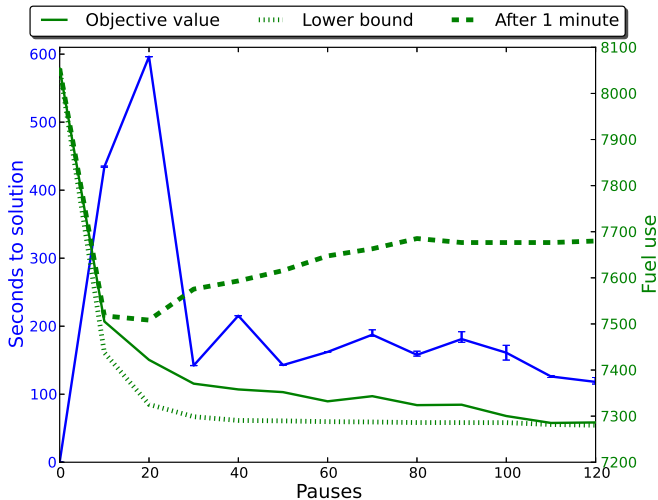
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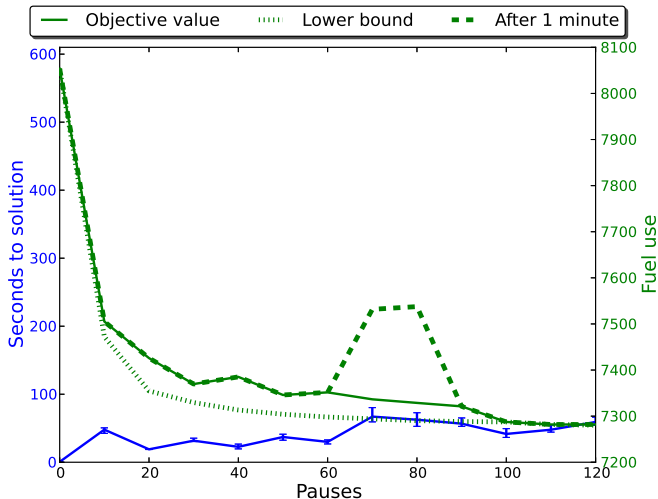


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Chicago, 100 vehicles, (20 from each of the 5 most common origin/destination pairs), stopping at 1% optimality gap

# Example solution times



Chicago, 100 vehicles, (20 from each of the 5 most common origin/destination pairs), stopping at 1% optimality gap, using lemmas

## Lemma

$$\max \{ T_v^O, T_w^O \} + M_{O_v, D_v} \leq \min \{ T_v^D, T_w^O \}. \quad (1)$$

### Lemma

*Let  $v, w \in V$  satisfying  $O_v = O_w$ ,  $D_v = D_w$ , and (1). Then if an optimal solution has  $q_{v,w,i,j} = 0$  for any edge  $(i,j) \in E$ , there exists an optimal solution with  $q_{v,w',i,j} = 0$  for all  $(i,j)$  all  $w'$  arriving later than  $w$ .*

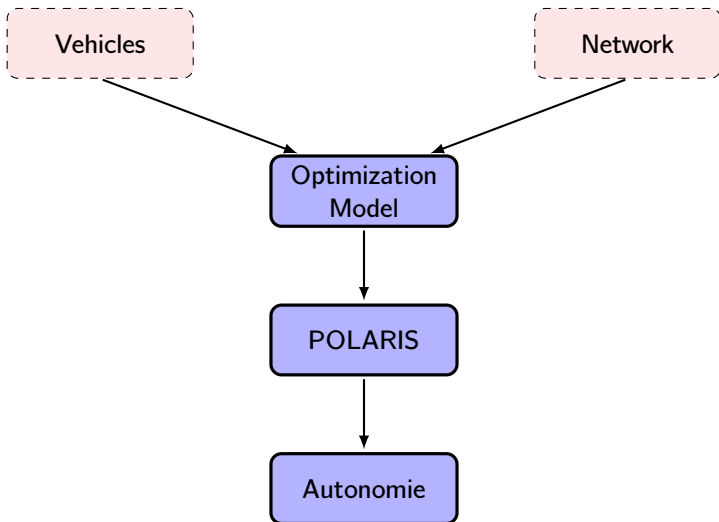


# Current work

- ▶ Non-free-flow speeds
- ▶ Graph-reduction techniques
- ▶ Larger problems
- ▶ <http://www.mcs.anl.gov/~jlarson/Platooning/>



# Workflow



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